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RESEARCH AND DEVELOPMENT OF SILICON SOLAR CELLS FOR A NEAR-SUN MISSION

Prepared for

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1. INTRODUCTION

This is the first bimonthly progress report on a program to investigate silicon solar cells for use in a near-sun mission. The objective of the program is to produce an optimum silicon solar cell and cover combination for a spacecraft designed to operate for one year in a highly elliptical orbit around the sun, in which the distance of the spacecraft will vary from 1 AU to 0.2 AU. The program is divided into four tasks.

TASK I

Consist of an analysis for the purpose of optimizing the short-circuit current at 1 air mass zero (AMZ) intensity, and the open-circuit voltage at 25 AMZ solar constants. The analysis assumes that radiative heat transfer and controlled variable angle of incident solar flux are the primary means of thermal control and considers all of the controllable variables of silicon cell manufacture and array assembly and their effects upon cell performance.

TASK II

Consists of preparation of specifications for materials and processing procedures, and a test plan that will define the fabrication of prototype silicon solar cells, and coverglass assemblies having characteristics based on criteria of the preceding analysis.

TASK III

Consists of the fabrication of cells on a pilot-line basis that will meet the criteria and specifications previously developed and will include the fabrication of cells having integral coverglasses. These coverglasses will be made up of SiO_2 and will be applied by using a proprietory process developed by the Librascope Division of General Precision, Inc., a subcontractor on this program.

TASK IV

Consists of testing the prototype solar cell assemblies and the evaluation of the design.

The work is being carried out as a joint effort of the Solid State Laboratory and the Power Systems Division of Electro-Optical Systems. Mr. Stephen Kaye is Project Supervisor; Mr. G. P. Rolik is responsible for cell analysis, design, and fabrication; Mr. Sanford Friedlander is responsible for mission analysis, cell evaluation, and testing.

2. PRESENT STATUS OF THE PROGRAM

The program is proceeding according to schedule. The Task-I analysis of the mission (and consequent cell design) has been completed, and a report has been prepared and submitted to the technical monitor for approval. Pending receipt of this approval, preliminary information required for Task II is being assembled so that upon receiving permission to proceed, this task can be completed as expeditiously as possible. No difficulties, either of a technical or scheduling nature, are presently foreseen.

3. SUMMARY OF TASK-I STUDY

The basic requirements of the Task-I study have already been discussed in Section 1 of this report. In this section, the requirements will be outlined in more detail, and a brief summary of the conslusions reached will be given together with a short discussion of the reasons for these conclusions.

It is specified that the analysis should consider the controllable variables in cell manufacture and array assembly--these variables to include dopant identity and concentration, diffusion process, junction depth, concentration gradient, cell thickness and resistivity, contact materials and the method of application, cell interconnection, contact geometry, cell-surface finish and antireflecting coating (if required), coverglass and coverglass attachment, and radiation degradation.

Previous work at EOS indicated the importance of minimization of series resistance for cells which were to be operated at high intensities. Bearing in mind the requirements for optimization of short-circuit current at 1 AU, and open-circuit voltage at .2 AU, while minimizing the radiation degradation, an analysis based on the cell having the following characteristics was developed:

(1)	Type:	n on p, 1 x 2 cm
(2)	Base Resistivity:	0.2 - 1.2 ohm-cm, boron doped
(3)	Diffusion:	phosphorus junction depth 0.6 - 0.8μM
(4)	Contact Geometry:	11 grids, with contact stripe along 2-cm side

The selection of n-on-p cells was based on their superior radiation resistance. The low series resistance requirement dictates the use of low resistivity base material; however, the use of material appreciably below 0.5 ohm-cm resistivity would not affect the series resistance (see Ref. 1). A further decrease in the resistivity of the base material would probably result in a decrease of the cell short-circuit current. The series resistance of cells made by a number of techniques was estimated using the calculations given in Ref. 1. These calculated and experimental values, where available, are shown in the following table:

TABLE 1

CALCULATED AND EXPERIMENTAL VALUES OF R_{tc} FOR VARIOUS TYPES OF CELLS

Base Material Resistivity ohm-cm	Sheet Resistance Diffused Layer per ohm square	Type Contact No. of Grids	Calc. Series Resistance	Meas. Series Resistance, Ref. 1)
10	40	nickel plated 5 grids	0.82 ohms	0.8-1.0
1	20	nickel plated 11 grids	0.25 "	0.3
1	20	sintered 11 grids	0.12 "	0.12 (estimated)
0.1	20	sintered 11 grids	0.1 "	--

Unfortunately, no data is available in the literature on the use of 2-cm cells at high intensities; therefore, we were unable to consider these cells in our analysis. Radiation degradation during the mission was taken into account by using the following equation:

$$Q = \left[\frac{7}{9}\left(\frac{\varphi}{\varphi_c}\right)^{\frac{1}{2}} + 1\right]^{-\frac{1}{2}} \qquad \text{Eq (1)}$$

where Q = fraction power remaining = $\frac{\text{final power}}{\text{initial power}}$

φ = integrated flux

φ_c = critical "flux to reduce cell power output," 25%

This equation was checked against experimental results obtained by W. Cherry (Ref. 2) and gives a very good fit to this data. The analysis assumed that an integral coverglass would be applied to the cell, thus avoiding the problems of degradation of the adhesive (darkening), which can be expected to occur when the cell is subjected to high intensity uv radiation. It was further assumed that this integral coverglass would be made of pure quartz (SiO_2), since this material provides good radiation protection and is not subject to discoloring that occurs in glass due to formation of "F" centers occuring at high-intensity illumination. Since the current state of the art in the application of such integral quartz covers limits the thickness to 50μM, this was the thickness assumed in the course of the further calculations. The minimum energy protons which would penetrate this thickness (or shielding) was estimated from the following equation:

$$E_p = 28.6 \times r^{0.558} \qquad \text{Eq. (2)}$$

where r = coverglass mean range in g/cm^2

The I-V characteristics of the cells were obtained from the standard diode equation (Ref. 3).

$$I = I_o\left[\exp\left(\frac{q(V - IR_{tc})}{AkT}\right) - 1\right] + \frac{V}{R_{sh}} - aJ_L \qquad \text{Eq. (3)}$$

where I = total current

I_o = saturation current

V = voltage

R_{tc} = series resistance

q = electronic charge

A = factor used to fit experimental curve to theoretical curve

k = Boltzmann's constant

R_{sh} = shunt resistance

a = active area contributing to light-generated current

J_L = light-generated current density

T = absolute temperature

The variation of light-generated current with temperature was calculated using Johnston's data (Ref. 4). The short-circuit current density was given by:

$$J_L = \frac{1.7}{1.8} (0.2214)\ L \left[1 + 8.668 \times 10^{-4} (T - 300)\right] \qquad \text{Eq. (4)}$$

where the factor 1.7/1.8 accounts for the difference between active areas of an 11-grid cell and a 5-grid cell used in Johnston's experiment, J_L is in mA/cm^2, L is in mW/cm^2, and T is in $^{\circ}$K. Several points from this equation were checked against Berman's data (Ref. 1).

The expression for the variation of open-circuit voltage as a function of temperature and intensity was derived from the work of Broder (Ref. 5) and is given by the following expression:

$$V_{oc} = \left[560 - 2(T - 300)\right] + 22.22 \ln \left[\frac{J(L, T)}{J(L=100, T)}\right] \qquad \text{Eq. (5)}$$

where V_{oc} is in millivolts, and the logarithmic expression is the increase in V_{oc} due to increased light intensity. This expression was also checked against Berman's data, and good agreement was obtained. In addition to these expressions, the following were also used in carrying out the complete mission analysis:

$$L = \frac{1}{R^2} \times 140 \cos\theta \qquad \text{Eq. (6)}$$

$$T = \left[\frac{L\left[M\,\alpha_{sc} + (1 - M)\,\alpha_p\right](1 - \eta)}{\left[M\,\epsilon_{sc} + (1 - M)\,\epsilon_{pb}\right]\sigma}\right]^{1/4} \qquad \text{Eq. (7)}$$

$$Q_V = 0.2\ Q_P \qquad \text{Eq. (8)}$$

$$Q_I = 0.8\ Q_P \qquad \text{Eq. (9)}$$

$$I_L = 2J\ (L, T) \qquad \text{Eq. (10)}$$

$$I_o = \frac{I_L}{\exp\left(\frac{q\ V_{oc}}{1000\ AkT\ -1}\right)} \qquad \text{Eq. (11)}$$

$$I = I_o\left\{\exp\left(\frac{S\left[V(T)\ - IR_s\right]}{1000\ AkT}\right) -1\right\} - I_L \qquad \text{Eq. (12)}$$

$$PA = 5 \times 10^3\ M(P_{mp}) \qquad \text{Eq. (13)}$$

θ	angle of incidence
L	solar intensity in mW/cm^2
R	distance from sun in AU
T	solar array temperature in ^oK
M	packing fraction
α_{sc}	solar cell absorptivity
α_p	solar panel absorptivity
η	average solar cell efficiency
e_{sc}	solar cell emissivity
e_{pf}, e_{pb}	solar panel emissivity, front and back
σ	Stefan-Boltzmann constant
Q_p	radiation degradation in power output
Ψ_r	total integrated proton flow in $protons/cm^2$
Ψ_c	critical proton flux for 25 percent degradation in power
Q_V	radiation degradation to voltage
Q_I	radiation degradation to current
J(L,T)	current density in mA/cm^2
V_{oc}	solar cell open-circuit voltage in mV
I_L	light-generated current in mA
I_o	reverse saturation current in mA
q	electronic charge
A	constant
k	Boltzmann's constant
I	solar cell current as a function of voltage in mA
R_s	solar cell series resistance in ohms
PA	specific power in $watts/meter^2$

In calculating the array temperatures that would result, the following values for the thermal properties of the solar cell/coverglass combination and array substrates were assumed:

Absorptivity of the solar cell	0.7
Emissivity of the solar cell	0.84
Absorptivity of solar panel substrate	0.35
Emissivity of solar panel substrate, front & back	0.9

The packing fraction or the ratio of total panel area to total cell area is assumed to be 0.9. The mission distance/time profile obtained from RFP A-11560(WEB-43) was used to calculate the panel output as a function of distance from the sun, which also incorporated radiation degradation as a function of mission duration.

The computer program was such as to output the V-I characteristics of the cells as a function of distance from the sun, angle of incidence, series resistance, and A factor; that is, the factor which appears in the exponent of the diode equation and from which the maximum power point for each of these curves was derived. Using this data, a series of four sets of curves were plotted and are seen in Figs. 1 - 4 showing the specific power putput in watts/meter^2 as a function of distance from the sun, with cell series resistance and A factor as parameters.

This brief discussion of the results of Task I has merely indicated the results obtained and the method by which they were achieved. Much additional detailed justification was included in the Task-I report that was submitted.

4. PLANNED WORK FOR NEXT REPORTING PERIOD

During the next reporting period, it is anticipated that a cell specification, fabrication schedule, fabrication procedure, and test plan for the optimum cell design will be submitted for NASA-Ames for approval and that the pilot run of prototype cells will begin. A midterm report and oral presentation will be given at NASA-Ames.

REFERENCES

1. P. A. Berman, "High Efficiency Silicon Solar Cells," Final Report; Heliotek Corp., Sylmar, Calif., Contract DA 36-039-sC-90777 (July 1964)

2. W. R. Cherry and L. W. Slifer, "Solar Cell Radiation Damage Studies with 1 MeV Electrons and 4.6 MeV Protons," Goddard Space Flight Center Report No. X-636-63-110 (May 1963)

3. M. B. Prince and M. Wolf, "New Developments in Silicon Photovoltaic Devices," Jour. Brit. IRE, Vol. 18, pp 583-595 (October 1958)

4. P. A. Johnston, "Laboratory Experiments on the Performance of Silicon Solar Cells at High Solar Intensities and Temperatures," NASA TN D-2733 (March 1965)

5. J. D. Broder, H. Kautz, J. Mandelkorn, L. Schwartz, and R. Ulman, "Solar Cell Performance at High Temperatures," paper presented at 4th Photovoltaic Specialists Conference at Lewis Research Center, Cleveland, Ohio; published in The Proceedings PIC-SOL 209/5 (Aug '64)

FIG. 1

Power Output vs Distance from the Sun

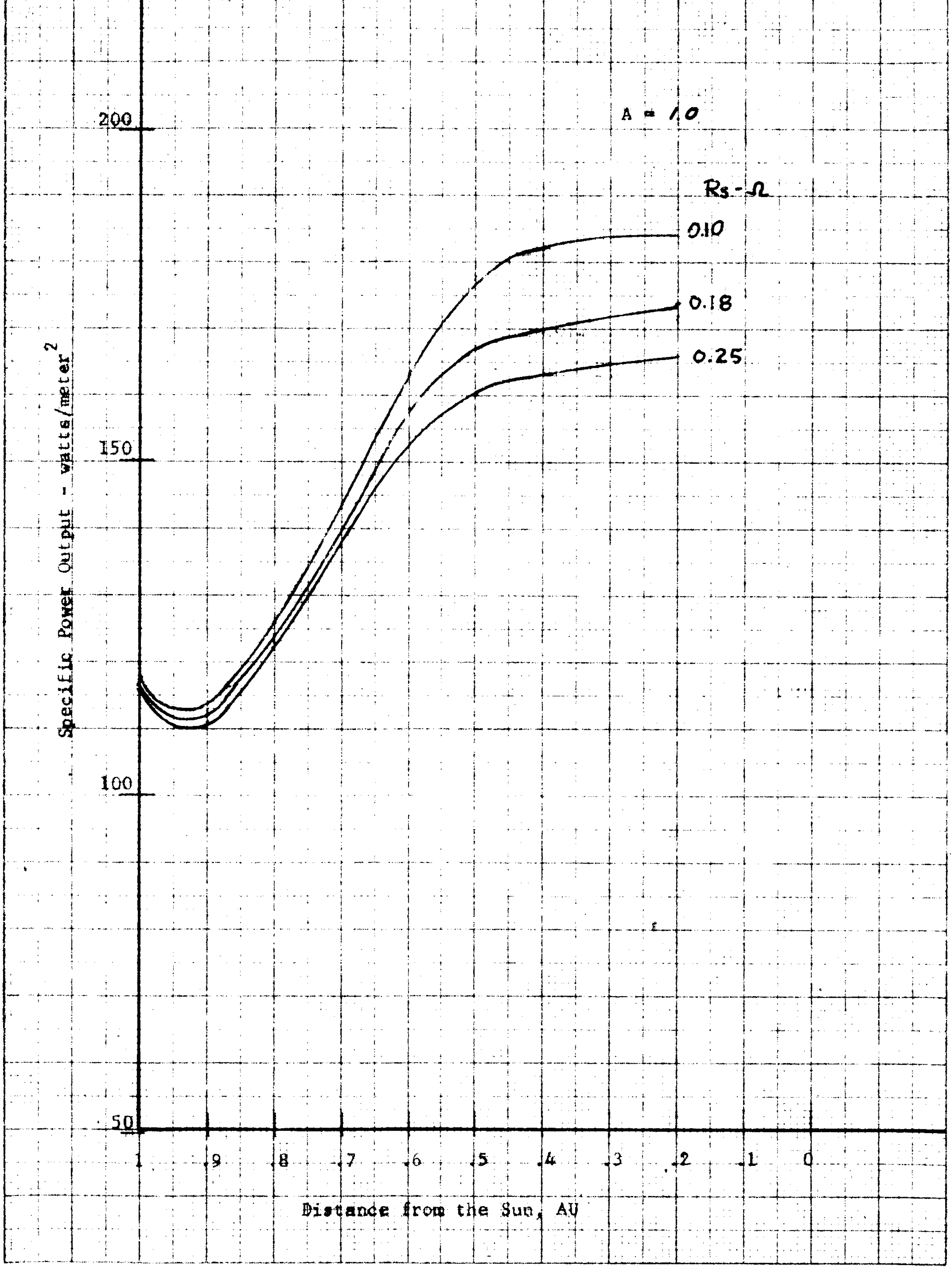

FIG. 2

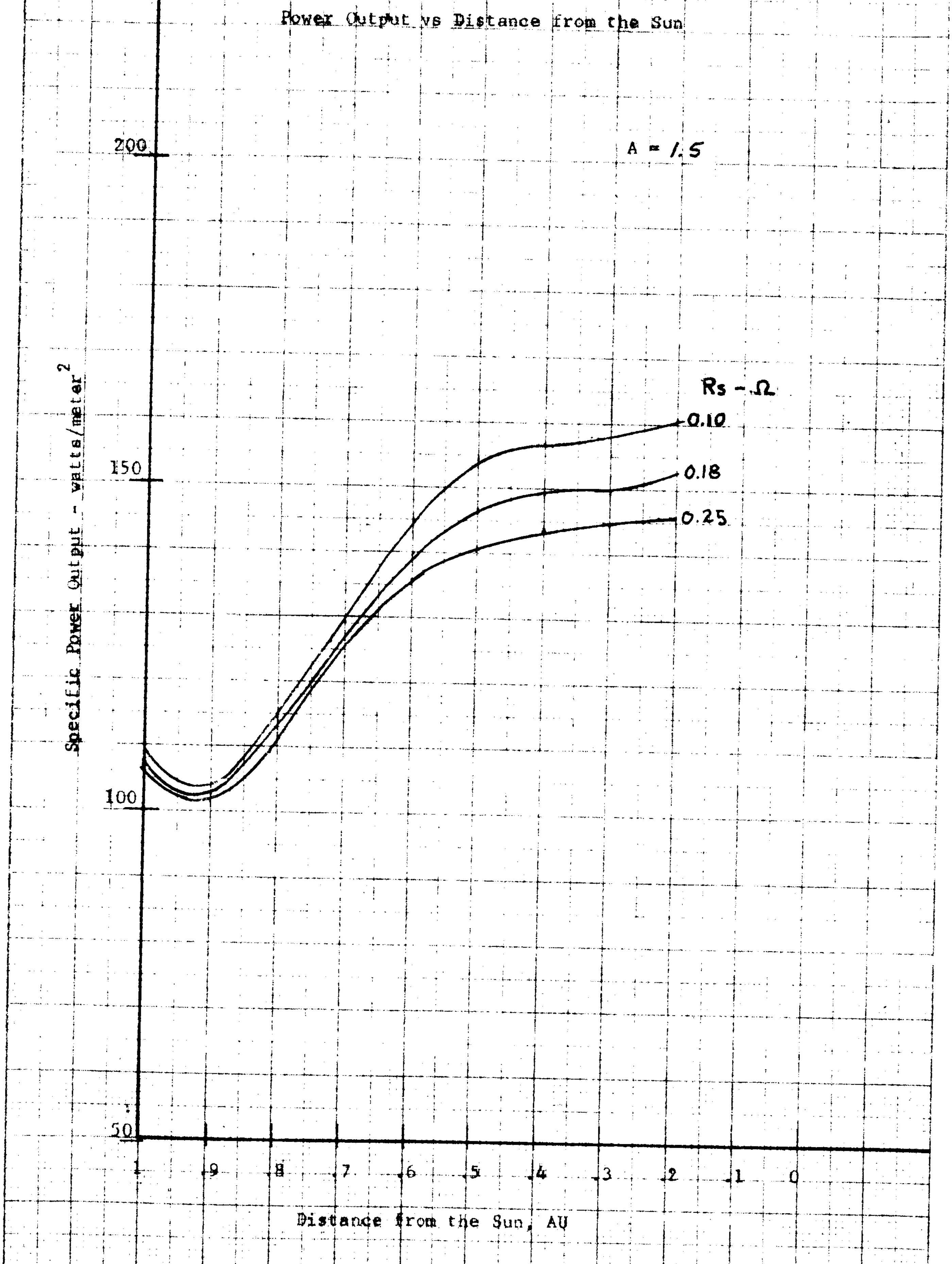
Power Output vs Distance from the Sun
A = 1.5
Rs - Ω
0.10
0.18
0.25
200
150
100
50
Specific Power Output - watts/meter^2
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Distance from the Sun, AU

FIG. 3

Power Output vs Distance from the Sun

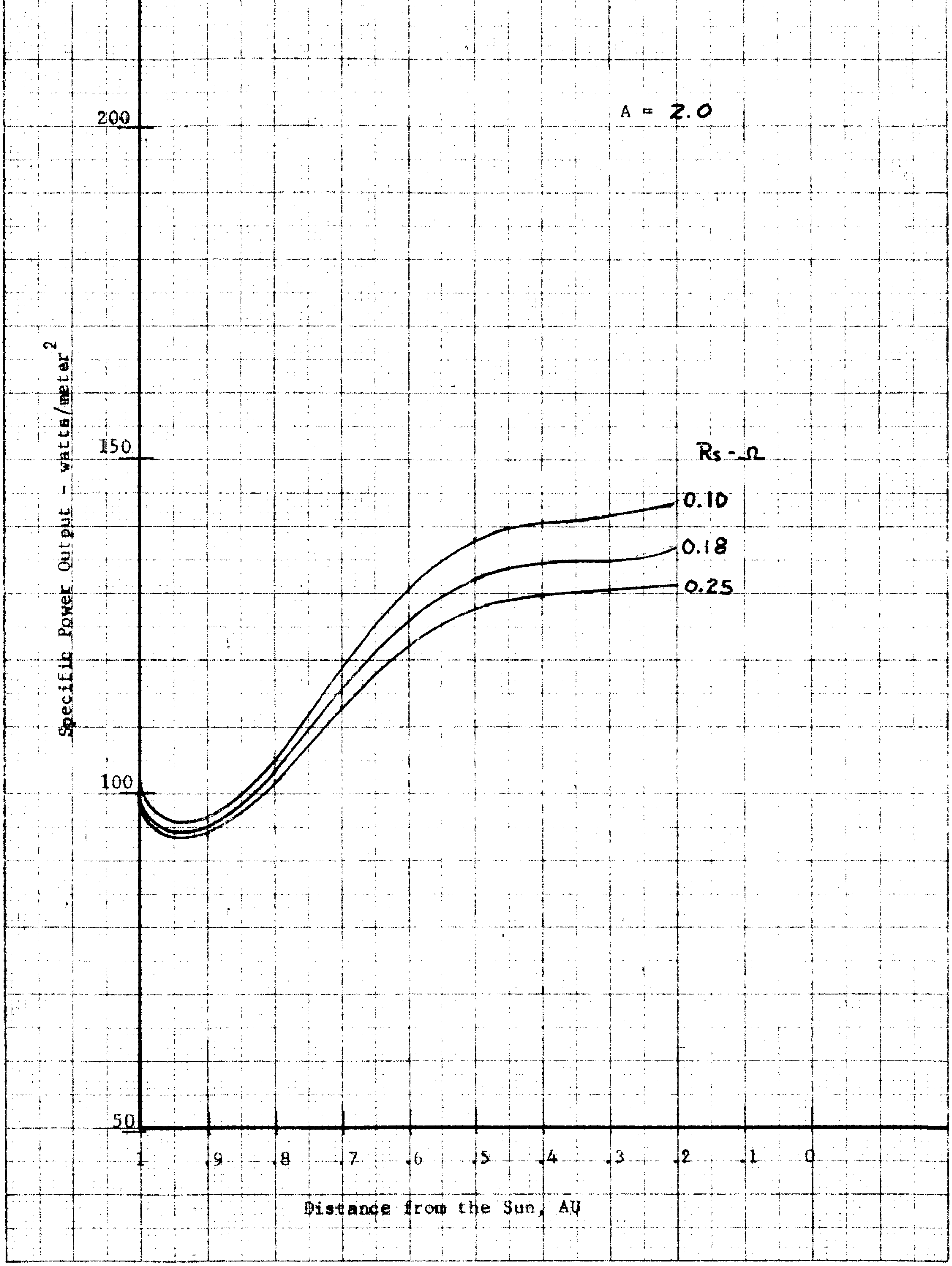

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FIG. 4

Power Output vs Distance from the Sun